Abstract

A laboratory scale rotating biological contactor (RBC) predenitrification system incorporating anoxic and aerobic units was evaluated for the treatment of settled high-strength municipal wastewater. The system was operated under four recycle ratios (1, 2, 3 and 4) and loading rates of 38–182 g COD/m² d and 0.22–14 g Oxid-N/m² d on the anoxic unit and 3.4–18 g COD/m² d and 0.24–1.8 g NH₄–N/m² d on the aerobic. The average removal efficiency in terms of chemical oxygen demand (COD), biochemical oxygen demand (BOD₅), total suspended solids (TSS) and total nitrogen (Total-N) was 82%, 86%, 63% and 54%; settling of the RBC effluent increased COD and TSS removal to 94% and 97%. An increase in hydraulic loading resulting from higher recirculation, had limited negative effect on organic removal but improved nitrogen removal, and in terms of Total-N removal efficiency increased up to a ratio of 3 and then decreased.

Keywords: Rotating biological contactor; Predenitrification; Nitrogen removal; Municipal wastewater

1. Introduction

Fixed-film systems have been successfully used for organic matter stabilization and nutrient control. Rotating biological contactors (RBC) have been employed in recent years for the treatment of various types of substrates, including municipal wastewater (Grady, 1983; Akunna and Jeffries, 2000; Griffin and Findlay, 2000; Nowak, 2000), and studies have been conducted to ascertain the effect on RBC performance of factors such as disc rotation speed (Friedman et al., 1979), recirculation (Klees and Silverstein, 1992), temperature (Pano and Middlebrooks, 1983), presence of organic particulate matter (Figueroa and Silverstein, 1992), hydraulic conditions (Kugaprasatham et al., 1991), use of supplemental air (Surampalli and Baumann, 1992) and scale-up (Wilson et al., 1980).

Biological nitrogen removal involves aerobic and anoxic conditions. Various schemes have been developed for nutrient control involving suspended or attached growth processes, and the RBC system has been used for this purpose. Carbon removal and ammonia nitrification have been studied in multi-stage RBC systems using synthetic (Weng and Molof, 1974; Stover and Kincannon, 1975) or municipal wastewater (Torpey et al., 1971; Murphy et al., 1977; Pano and Middlebrooks, 1983), and the effect of the organic strength/ NH₄–N ratio on the process has been examined (Okabe et al., 1996; Radwan and Ramanujam, 1997). Denitrification is accomplished through the addition of an anoxic step following or preceding the aerobic step (post or predenitrification). Postdenitrification in the RBC process has been developed since the late 1970s (Murphy et al., 1977; Soyupak and Murphy, 1979), and involves the addition of an external carbon source (such as methanol). Predenitrifieration does not require the addition of external carbon, but depends on the recycle of effluent to the anoxic unit; this method has been mainly employed in the activated sludge process and limited work has been carried out on biofilm reactors, including RBC (Tzimas and Grigoropoulos, 1996) and moving-bed systems (Rusten et al., 1995). Finally, simultaneous nitrification and denitrification accompanied by carbon removal has been reported in single or multi-stage RBC configurations (Watanabe et al., 1994; Gupta and Gupta, 1999).
The aim of this research work was to study a simple, low cost two-stage RBC system, consisting of single-stage anoxic and aerobic reactors, for the treatment of settled high-strength municipal wastewater, and to evaluate its performance under various hydraulic and organic loading conditions and recycle ratios.

2. Methods

2.1. Experimental system

The two-stage RBC system consisted of an anoxic and an aerobic reactor made of plexiglas (Fig. 1). The covered anoxic unit had a 1.0-l working volume; four fully immersed biodisks, 7 cm in diameter and with a 0.0343-m² total surface area, were connected via a stainless steel shaft to a motor and rotated at 2 rpm parallel to the direction of wastewater flow. Influent waste and recycled effluent were fed to the unit through inlet ports in the cover and its effluent was directed by gravity to the top of the 2.75-l open aerobic unit. This unit had four disks 20 cm in diameter and nine rectangular blades 6×2.1 cm placed in the disk interval space to enhance mixing; the total biomass support surface was 0.2966 m², and the disks were 35% submerged (based on disk surface) and rotated at 8 rpm in the direction of flow. The high rotational speed, selected to prevent the significant solids accumulation noted in a previous study at 4 rpm (Tzimas and Grigoropoulos, 1996), resulted in elevated dissolved oxygen (DO) concentrations. Two variable-speed peristaltic pumps, activated by a timer for appropriate periods, were used to feed settled municipal wastewater and recycle effluent to the anoxic contactor, and treated effluent was collected by gravity; 10-l glass carboys were used as holding vessels and the influent vessel was magnetically stirred. Part of the RBC effluent on several occasions was settled in a 1-l Imhoff cone for 1 h in order to evaluate the effect of secondary sedimentation on effluent quality.

2.2. Oxygen transfer

The RBC system was evaluated for oxygen transfer using tap water, and the procedure employed involved filling the units, depleting the DO in the water to zero via the addition of a reducing agent (110–150 mg/l sodium sulphite) and a catalyst (1.3 mg/l cobalt chloride), setting the disks in motion and measuring the DO concentration and temperature at frequent intervals with a DO probe (WEF, 1988). The DO level in the anoxic unit was very low and oxygen transfer in the aerobic unit was high; the oxygen transfer rates which were computed averaged 1.04 and 212 mg O₂/h in the two units, respectively.

2.3. Analytical techniques

All analytical procedures were performed according to Standard Methods (APHA, 1992). Chemical oxygen demand (COD) was measured by the open reflux method and soluble COD (SCOD) was determined by
the same procedure using a sample passed through a membrane filter; biochemical oxygen demand (BOD<sub>5</sub>) was measured by the 5-d BOD test using the azide modification of the iodometric method for DO determination and total suspended solids (TSS) were measured by the gravimetric method. Ammonia nitrogen (NH<sub>4</sub>–N) was determined by the titrimetric method after a preliminary distillation step and total Kjeldahl nitrogen (TKN) was measured using the macro-Kjeldahl procedure; total phosphorus (Total-P) was determined using the persulfate digestion method and ascorbic acid colorimetric technique. Alkalinity was measured titrimetrically, while pH, DO and temperature were determined using portable pH and DO meters. Finally, oxidized nitrogen (Oxid-N, the sum of NO<sub>2</sub>–N and NO<sub>3</sub>–N) was measured by the Devarda’s alloy reduction method based on the conversion of Oxid-N to NH<sub>4</sub>–N (APHA, 1985).

2.4. Wastewater

Municipal wastewater was collected from a central sewer in the city of Patras as the treatment facility for this city of 168,000 people, an activated sludge-type plant, had been under construction at that time. The raw wastewater was relatively strong and had the following average characteristics in mg/l: COD 833, SCOD 242, TSS 424, NH<sub>4</sub>–N 42, TKN 64, Total-P 5.4 and alkalinity 375 (as CaCO<sub>3</sub>); considering a net loss of 3.85 mg/mg NH<sub>4</sub>–N (Henze et al., 1995), alkalinity was adequate for the biological conversion of nitrogen. The RBC system was fed presettled (in a bucket for 2 h) wastewater. Primary sedimentation resulted in average COD and TSS removals of 26% and 52% but had a negligible effect on the nutrient content.

2.5. RBC start-up

Reactor start-up involved daily feeding of raw wastewater to both the anoxic and aerobic units (starting with clean tanks and disks) which were operated independently in a fill and draw mode for 9 d; feeding stopped and continuous recirculation of effluent followed in each unit for 5 d. At the end of this 14-d period, biofilm had started to form on the disks, especially in the aerobic unit, and the reactors were thereafter operated in series in the continuous flow test mode.

2.6. Operational conditions

The study was conducted for a period of 4.5 months (November 1997–April 1998) and operational characteristics for the experimental units are given in Table 1. The RBC system was loaded with 4 l/d, except for short periods, and recycle was applied at 1, 2, 3 and 4 times the influent rate in order to ascertain the optimum level for combined organic and nitrogen removal.

3. Results

3.1. General performance

The daily variations in COD, SCOD and TSS values and in NH<sub>4</sub>–N, Oxid-N and Total-N values for the RBC system influent, intermediate (anoxic effluent) and effluent are shown in Figs. 2 and 3; daily average samples of the influent and effluent and grab samples of the anoxic effluent were tested. From the first days of operation effluent COD was at a low level, below 100 mg/l; however, during two periods (days of operation 65–78 and 102–126) effluent quality deteriorated as a result of the washout of detached biomass. This conclusion is supported by the corresponding low SCOD values (19–52 mg/l) and the parallel data obtained after effluent sedimentation. The effluent TSS values were lower than those in the intermediate sample, except during the two periods of biomass loss. Nitrification gradually increased in the aerobic RBC, and after the 60th day of operation the NH<sub>4</sub>–N concentration in the effluent remained at an average level of 0.6 mg/l.

3.2. Loading and test conditions

The average loading rates and general control data for the test reactors are given in Table 2. The DO concentration was kept below 0.6 mg/l in the anoxic unit but remained at an elevated level in the aerobic unit, while temperature was essentially maintained above 13 °C; also pH and alkalinity were in the appropriate range for the biological processes involved. The organic loading to the aerobic reactor averaged 5.9 (3.8–10) g BOD<sub>5</sub>/m<sup>2</sup> d; this was higher than the level applied in a previous study using the same experimental model, 2.5–5.0 g BOD<sub>5</sub>/m<sup>2</sup> d (Tzimas and Grigoropoulos, 1996), but still in the lower range of values generally accepted for secondary treatment with nitrification, 7.0–15 g BOD<sub>5</sub>/m<sup>2</sup> d.
The anoxic reactor was loaded at an average value of 4.9 (0.22–14) g Oxid-N/m² d, which was at the level applied in the previous work and higher than the 2.88 g Oxid-N/m² d value reported in an earlier study (Soyupak and Murphy, 1979).

Table 2

<table>
<thead>
<tr>
<th>Operational or loading value</th>
<th>Anoxic contactor</th>
<th>Aerobic contactor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Average</td>
</tr>
<tr>
<td>pH</td>
<td>7.2–7.8</td>
<td>7.1–8.1</td>
</tr>
<tr>
<td>Alkalinity, mg/l as CaCO₃</td>
<td>0.0–0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>DO, mg/l</td>
<td>13.8–20.9</td>
<td>17.0</td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>233–583</td>
<td>378</td>
</tr>
<tr>
<td>Hydraulic loading, l/m² d</td>
<td>COD 38–182</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>BOD₅ 30–94</td>
<td>59</td>
</tr>
<tr>
<td>Organic loading, g/m² d</td>
<td>Oxid-N 0.22–14</td>
<td>4.9</td>
</tr>
</tbody>
</table>

*Measured in the effluent.

Fig. 2. Variation in the organic and solid content.

Fig. 3. Variation in the nitrogen content.
3.3. Organic and nitrogen removal

The influence of the hydraulic loading on the RBC system performance is shown in Fig. 4. In the anoxic unit the removal of Oxid-N decreased (to 50%) at the 466 l/m² d rate (recycle ratio 3), while at the other rates it remained at about 65%; and the removal of COD decreased (from 46% to 31%) with increased hydraulic loading. In the aerobic unit COD removal was greatly influenced by the increase in hydraulic loading, and at a rate of 54 l/m² d (recycle ratio 3) it appeared to be only 7%; however, during this period intense separation of the attached biomass occurred contributing to high effluent COD values, and the low removal efficiency was the result of biosolids escape rather than inadequacy of the unit at this high loading. Settling of the effluent for 1 h yielded additional COD and TSS removals of 67% and 89%. Nitrification efficiency increased with recycle ratios up to 2, from 63% to 98% (at ratios 1 and 2); thereafter it remained at that level and seemed to be independent of biomass detachment. Total-N removal in the RBC system increased with recycle up to a level of 3, but dropped at a ratio of 4, while COD removal generally decreased with recycle increase. It should be noted that the hydraulic loading rate was essentially controlled by the recycle ratio, as the wastewater feed rate remained constant at 4 l/d, corresponding to a 22.5-h hydraulic retention time (HRT) based on the total working volume of the two units.

3.4. Overall performance

The average RBC system influent and effluent quality characteristics and the corresponding removal efficiencies are given in Table 3. The removal of COD and TSS ranged from 53.3% to 95.5% and from negative to 96.2%; however, taking into consideration the effect of effluent settling during the periods of biosolids washout, COD and TSS removal increased to approximately 94% and 97%, yielding acceptable effluent discharge concentrations. The reduction in NH₄-N averaged 92.8%, while

Table 3
Average quality characteristics and removal efficiency

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Influent (mg/l)</th>
<th>Effluent (mg/l)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Average</td>
<td>Range</td>
</tr>
<tr>
<td>BOD₅</td>
<td>199–521</td>
<td>382</td>
<td>23–98</td>
</tr>
<tr>
<td>COD</td>
<td>294–822</td>
<td>618</td>
<td>34–283</td>
</tr>
<tr>
<td>SCOD</td>
<td>167–305</td>
<td>226</td>
<td>19–52</td>
</tr>
<tr>
<td>TSS</td>
<td>53–400</td>
<td>199</td>
<td>4–357</td>
</tr>
<tr>
<td>NH₄–N</td>
<td>27–73</td>
<td>43</td>
<td>0–29</td>
</tr>
<tr>
<td>TKN</td>
<td>39–118</td>
<td>61</td>
<td>2.6–38</td>
</tr>
<tr>
<td>Oxid-N</td>
<td>0–3.4</td>
<td>&lt;0.5</td>
<td>0.8–50</td>
</tr>
<tr>
<td>Total-N</td>
<td>39–118</td>
<td>61</td>
<td>12–64</td>
</tr>
<tr>
<td>Total-P</td>
<td>5.5–6.4</td>
<td>6.0</td>
<td>5.5–6.2</td>
</tr>
</tbody>
</table>
the average loading rate was 0.99 g NH₄-N/m² d. Torpey et al. (1971) have reported a 56% NH₄-N removal in a 10-stage RBC system at a loading level of about 1.0 g NH₄-N/m² d, while Pano and Middlebrooks (1983) using a four-stage RBC at 15 °C and loadings of 0.387–1.563 g NH₄-N/m² d obtained NH₄-N removals ranging from 86.9% to 98.1%. Also, Klees and Silverstein (1992) have reported that the maximum NH₄-N removal rate achieved in their study was 1.945 g/m² d at a hydraulic loading of 0.245 m³/m² d and a recycle ratio of 1, while the maximum BOD₅ removal was 1.108 g/m² d at an organic loading of 1.678 g/m² d. Griffin and Findlay (2000) have suggested that in conventional RBC reactors the organic loading should be at levels of 4 or 2.5 g BOD₅/m² d in order to meet effluent requirement of 15 or 10 mg NH₄-N/l, and Nowak (2000) has proposed that in single-stage RBC reactors an organic loading of 2.5 g BOD₅/m² d is desirable to achieve an effluent NH₄-N concentration below 5 mg/l at temperatures above 12 °C.

3.5. Biomass development and characteristics

The biomass developed in the aerobic unit did not always cover the entire disk surface, and because of the increased rotational speed used in this study detachment occurred. Biomass development in the anoxic unit was more uniform and solids accumulated at the bottom of the reactor; consequently in order to improve efficiency, solids were removed two times during the test period. At the end of the study the biomass attached to the rotating disks and blades (and the tank surfaces) and suspended in the mixed liquor in the two RBC units was collected, dried, weighed and characterized. The attached biomass in the anoxic and aerobic units had a 74% and 78% volatile fraction and on a dry basis contained 2.55 and 2.66 mg/mg COD, 0.055 and 0.124 mg/mg TKN and 0.0080 and 0.0068 mg/mg Total-P. Pano and Middlebrooks (1983) have reported that the volatile fraction of attached biomass decreased from 68% to 61% in a four-stage aerobic RBC system, while the carbon/nitrogen/phosphorus ratio was 28/5.2/1. Based on a material balance throughout the study, the total (attached and suspended) biomass yield was estimated to be 0.015 and 0.027 g/g COD removed in the anoxic and aerobic reactors, reflecting a twofold increase in the latter unit.

4. Discussion

4.1. Effect of the organic strength to nitrogen ratio

The COD/NH₄−N ratio in the wastewater fed to the aerobic reactor (based on the anoxic unit effluent) had an average value of 9.9 (ranging from 4.5 to 20.4). It should be noted that according to Radwan and Ramanujam (1997), who treated medium-strength syn-

thetic wastewater, at a COD/NH₄−N ratio below 23 nitrification decreased when the rotational speed was 6 rpm and increased when it was 12 rpm (it was 8 rpm in the present study). Watanabe et al. (1994), who used a single reactor with partially and fully submerged discs, have found that at an influent carbon/nitrogen (C/N) ratio of 3.5, Total-N removal efficiency was 60% with a HRT of 12 h and loadings of total organic carbon (TOC) and NH₄-N to the partially submerged disks 2.3 and 1.1 g/m² d, respectively; further Okabe et al. (1996) have stated that a C/N ratio of 1.5 resulted in retardation of the NO₂ oxidizers. The COD/Total-N ratio in the settled municipal wastewater fed to the system averaged 10.5 (3.3–15.0) while the SCOD/Total-N ratio averaged 4.0 (3.0–4.6). Rusten et al. (1995), who used a moving-bed biofilm reactor to treat dilute municipal wastewater, have reported that in the pre-denitrification mode and at an optimum recirculation ratio of 2, a HRT of 6.5 h and a BSCOD/Total-N ratio of 2, Total-N removal was 64% (higher than the 54% average value observed in this work). Rusten et al. defined biodegradable soluble COD (BSCOD) as the difference between influent SCOD and effluent SCOD from the last nitrifying reactor in the system and considered it to be a measure of the suitability of the wastewater as a carbon source; the BSCOD/Total-N ratio in this study averaged 3.4 (2.4–4.1) indicating that the wastewater used had a high concentration of available SCOD.

4.2. Effect of loading and recycle

The effect of the loading rate (in terms of COD or Total-N) on the RBC system performance (as indicated by the corresponding removal rates) is presented in Fig. 5, where values are computed on the basis of feed wastewater characteristics and rate. The COD data show a high degree of dependence (a correlation coefficient of 0.9703), however, the Total-N data do not exhibit similar behavior (a coefficient of 0.4608). This may be attributed to a lower rate of denitrification taking place in the relatively undersized anoxic contactor of the experimental system; it should be mentioned that the aerobic/anoxic disk area ratio was 8.6, higher than the experimental system; it should be mentioned that the aerobic/anoxic disk area ratio was 8.6, higher than the ratio of 5.0 recommended by Tzimas and Grigoropoulos (1996) on the basis of an analysis of nomograms for size selection of independently operated RBC nitrification and denitrification units (Metcalf and Eddy et al., 1991). Multiple regression analysis carried out for the total RBC system (anoxic-aerobic) to relate removal rate with loading rate and recycle ratio gave the following relationships,

\[
\begin{align*}
\text{ORR} &= 0.80 \text{OLR}^{1.06} \text{NLR}^{-0.017} R^2 = 0.975 \\
\text{NRR} &= 0.431 \text{NLR}^{1.29} \text{NLR}^{0.319} R^2 = 0.577
\end{align*}
\]

where ORR and OLR are the organic removal and organic loading rates (g COD/m² d), NRR and NLR are
the nitrogen removal and nitrogen loading rates (g Total-N/m² d) and \( r \) is the recycle ratio. It should be noted that the removal and loading rates in Eqs. (1) and (2) are based on the wastewater feed rate (4 l/d). The removal rate for both COD and Total-N was mainly affected by the corresponding loading rate, and recycle had a negligible negative effect on COD removal but a significant effect on Total-N removal. The relationship of the Total-N removal rate with both the nitrogen and organic loading rates and recycle is given in Eq. (3), where the COD loading rate has a negative effect:

\[
\text{NRR} = 0.753 \cdot \text{NLR}^{1.410} \cdot \text{OLR}^{-0.233} \cdot r^{-0.312} \quad R^2 = 0.688 \quad (3)
\]

Regression analysis applied individually to the anoxic and aerobic unit data indicated that an increase in the COD loading rate caused a decreased NH₄-N removal rate in the aerobic reactor and an increased Oxid-N removal rate in the anoxic reactor. Findings reported by Pano and Middlebrooks (1983) and Klees and Silverstein (1992) for four-stage RBC reactors treating municipal wastewater also indicate that the amount of NH₄-N removed decreased with organic loading.

5. Conclusions

The RBC anoxic-aerobic system was operated at a constant settled municipal wastewater feed rate of 4 l/d (a total HRT of 22.5 h) and varying effluent recycle ratios (1–4 times), with the fully and partially (35%) immersed biodisks rotating at 2 and 8 rpm. The organic and nitrogen loading rates applied averaged 104 g COD/ m² d (59 g BOD₅/m² d) and 4.9 g Oxid-N/m² d in the anoxic unit and 9.2 g COD/m² d (5.9 g BOD₅/m² d) and 0.99 g NH₄-N/m² d in the aerobic. The COD removal efficiency was in the range of 53.3–95.5%, averaging 82.3%; the lower values were attributed to biomass detachment and loss in the aerobic unit resulting from the high disk rotational speed, and were accompanied by the increased presence of TSS in the effluent. Secondary settling improved system efficiency to a level of 94% and 97% in terms of COD and TSS. The removal of nitrogen effected by the system averaged 92.8% in terms of NH₄–N and 54.0% in terms of Total-N. An increase in the hydraulic loading rate resulting from higher recirculation rates, caused a slight reduction in organic removal but improved nitrogen removal; in terms of NH₄–N removal increased up to a recycle ratio of 2 and then remained constant, while in terms of Total-N it increased up to a ratio of 3 and then decreased.

References


